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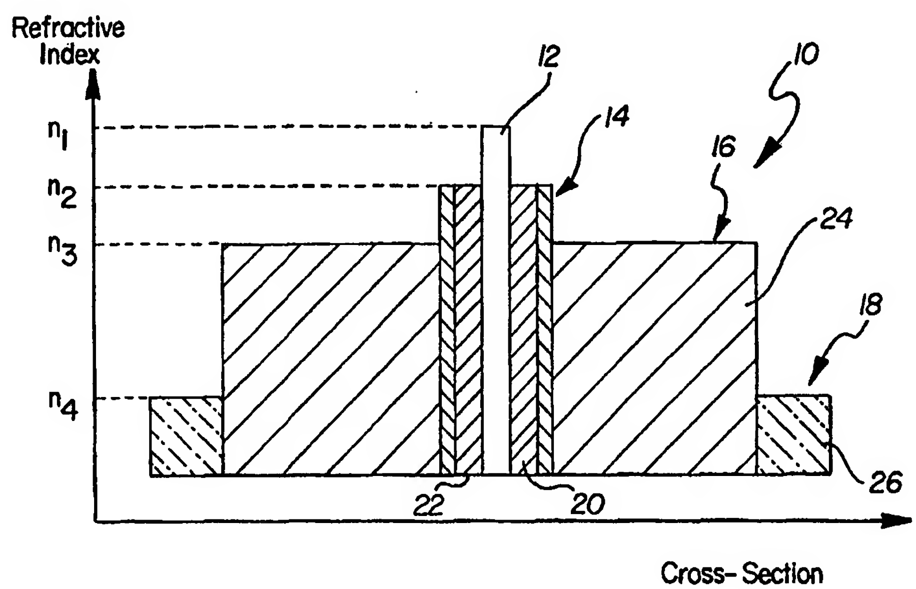

(57) Abstract

An optical fiber (10) made with a central core (12), a first cladding layer (16), and a second cladding layer (18) having a series of perturbations or irregularities formed into the otherwise generally circular outer boundary of the first cladding layer. The irregularities in the first cladding layer interrupt the propagation of skew rays and encourage coupling into the core. The irregularities are formed by drilling holes (44-58) in the fiber preform, which are parallel with its longitudinal axis, and inserting rods therein. An intermediate cladding layer (14) is provided for suppressing higher order core modes. The optical fibers are used in cladding pumped fiber lasers and amplifiers.

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DOUBLE-CLAD RARE EARTH DOPED OPTICAL FIBERS

FIELD OF THE INVENTION

The instant invention relates to double clad optical fiber optimized for use in, for example, fiber lasers and amplifiers, as well as methods of manufacture and uses therefor.

BACKGROUND OF THE TECHNOLOGY

Optical amplifiers, and in particular the optically-pumped erbium doped fiber amplifier (EDFA), are widely used in fiberoptic transmission systems (see, for example, E. Desurvire, Erbium Doped Fiber Amplifiers, Wiley, New York, 1994). In a typical device, a weak 1550 nanometer (nm) optical signal and a strong 980 nm pump signal, both propagating in single-mode optical fiber, are combined by means of a fused dichroic coupler into one single-mode fiber. This fiber is then coupled to a single-mode erbium-doped fiber where the erbium ions absorb the pump radiation and provide gain at the signal wavelength. The result is that the output of the EDFA is an amplified replica of the input signal. Such amplifiers are useful for overcoming the various losses that occur an any fiberoptic transmission system.

In a conventional fiber amplifier, the pump source consists of a laser diode operating in a single transverse mode coupled to single-mode optical fiber. The amount of optical power that can be obtained from such devices is limited by the power density at the output facet of the pump laser. To increase the diode output power, it is necessary to increase the emitting area of the diode. Unfortunately, when this is done, the transverse mode structure of the resulting broad area laser becomes multimode, and the laser output is no longer sufficiently coherent to be coupled into a single-mode fiber. Such a diode output can, however, be coupled into a multimode fiber, to provide an essentially incoherent source for pumping the amplifier. Such multimode fibers are typically round, since this shape is easier to fabricate than any alternative shape.

In a variation of this design, ytterbium may be added to the fiber (as taught in, for example, US patent no. 5,225,925, to Grubb, et al. issued Jul. 6. 1993). In the optimized fiber disclosed in the '925 patent, energy absorbed by the ytterbium ions is efficiently transferred to the erbium ions. This results in a fiber with a much stronger, broader absorption than can be obtained in a singly-doped erbium fiber. An amplifier made from such fiber (a ytterbium-erbium doped fiber amplifier or YEDFA), can be pumped with longer wavelength sources, such as a diode-pumped neodymium laser (see Grubb, et al. Electronics Letters, 1991); output powers in excess of 4 watts (w) have been reported (Grubb, et al. paper TuG4 OFC 1996). The wavelengths of neodymium lasers used for this purpose has varied from 1064 nm in Nd:YAG to 1047 nm in Nd:YLF. Over this range in a typical fiber, the Yb absorption varies from 2 to 7 dB/m. For comparison, in the same fiber at 950 nm the absorption was 420 dB/m and at 975 nm it was 2500 dB/m.

Techniques also exist for pumping an amplifier directly with multimode diodes. US patent no. 3,808,549, issued April 30, 1974, to Mauer discloses a design in which a small, strongly absorbing, single-mode core is embedded in a large, multimode waveguide. With all modes excited, the optical power density in such a double clad waveguide is nearly uniform across the waveguide aperture. Under these conditions, the average absorption coefficient is approximately equal to the absorption coefficient of the core, normalized by the area ratio of the two waveguides. Radiation propagating in modes that overlap the doped region will be preferentially absorbed, and some form of mode mixing is often required to maintain the uniform power distribution required to ensure that all the power in the multimode waveguide will eventually be absorbed by the core.

Using a double clad design of this type, Minelly, et al. (IEEE Photonics Technology Letters, 5(3), 301-303, 1993) demonstrated a YEDFA pumped with a broad area laser diode. Minelly, et al. used bulk optics to couple the output of a laser diode array to the double-clad fiber, and geometries using fused or reflective couplers similar to those used for conventional single-mode amplifiers can also be used. With some modification, for example, the filter

wavelength division multiplexer (FWDM) made by E-Tek Dynamics Inc. of San Jose CA could be used as a multimode coupler. This, combined with a double clad gain fiber would permit a multimode-pumped amplifier to be built in the same geometry as the conventional EDFA described above.

The fiber shown by Mauer was round with a concentric core, as was the fiber used by Minelly, et al. This is a very inefficient shape for a double clad device. As noted by Snitzer et al. (US patent nos. 3,729,690, April 24, 1973 and 4,815,079, March 21, 1989), in a double clad fiber with radial symmetry, many of the modes in the multimode waveguide do not interact with, and are not absorbed by a concentric core. This phenomenon can also be described by geometrical optics, where it would be observed that the vast majority of the guided rays are skew rays that never pass through the core. This problem is a result of radial symmetry, and can be eliminated by perturbations that break this symmetry. Snitzer et al. proposed the use of an off-center, circular waveguide as well as a rectangular guide with two different transverse dimensions. Additionally, Lewis, et al. in US Patent No. 5,418,880 and Muendel in US Patent No. 5,533,163 teach the use of various space filling polygons. Such shapes are limited to triangles, certain symmetric quadrilaterals and regular hexagons.

The techniques used to make fibers with these shapes generally resulted in polymer-clad fibers that were not round or which had a single-mode core that was not concentric with the fiber. Polymer-clad fibers are less stable thermally and mechanically than silica fibers, and they can be easily damaged by the pump radiation. Non-concentric fibers are difficult to align and splice. The fact that the fibers are not round makes it difficult to combine these fibers with more standard fiber components, and to exploit the existing infrastructure of tools such as fiber cleavers, splicers and ferrules that are optimized for use round optical fibers. For practical applications, it is important to utilize a shape that can be surrounded by a thickness of low-index silica outer cladding with a round outer diameter. Typical 100/125 multimode fiber has a 12.5 micron (μm) cladding thickness. The maximum

outer radius of the waveguide is constrained by the desired outer diameter minus the cladding thickness.

Multimode pump sources and couplers are also optimized for round fiber. To efficiently couple a round multimode pump fiber to a non-circular gain fiber, it is important that the pump fiber diameter be less than or equal to the minimum inner diameter of the low-index silica outer cladding. Any radial perturbation in such fibers will be constrained to an annular region whose inner diameter is limited by the pump fiber diameter and whose outer diameter is limited by the fiber outer diameter and cladding thickness. The constraints on actual fibers are such that the radial dimension of the waveguide can only vary by ±10%, with values as small as ±5% being preferable in some cases. There is therefore a need for fibers that appear externally as round, concentric, all-silica fibers, but which nonetheless have been sufficiently perturbed to allow efficient double-clad absorption to occur.

Finally, it is important to recognize that double clad fibers are not truly single mode fibers. The same perturbations that allow efficient absorption also ensure that many guided modes at the signal wavelength will have appreciable overlap with the fiber core. This is often not a problem in a fiber laser, because the modes that oscillate will be those that most efficiently overlap the core region. However, in an amplifier, signal power that is coupled into the multimode waveguide could give rise to signal distortions when this signal is accidentally amplified and coupled back into the output signal. There is clearly a need for fibers that prevent these parasitic processes from occurring.

Accordingly, there exists a need for enhanced optical fibers in which guided rays propagating along the length of the fiber are passed through the fiber core. The enhanced fiber should retain the preferred round shape to remain compatible with other fiber components, as noted above. Likewise, the core of the fiber should preferably be substantially in the center of the fiber.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a double-clad optical fiber structure that allows pump radiation propagating in a multimode waveguide to be absorbed into a single-mode core.

It is another object of the invention to provide a double-clad optical fiber structure that allows amplification of optical signals propagating in the fundamental mode of the structure while suppressing parasitic amplification of other modes.

In accordance with these and other objects of the invention that will become apparent from the description herein, an optical fiber coupler comprises: a central glass core, doped to absorb radiation at a pump wavelength and to provide gain at a signal wavelength, a first glass cladding layer that, at the pump wavelength, is transparent and that, at the signal wavelength, optimizes coupling and amplification for the fundamental mode while minimizing coupling and amplification for other modes, and a second glass cladding layer with a noncircular outer boundary that is still near enough to round and concentric that a round outer cladding is possible.

The fiber may include a third cladding layer, that has an inner boundary that conforms to the outer boundary of the second cladding and that has a round outer diameter.

A method for making the optical fiber coupler according to the invention includes a sequence of procedures where the core and first cladding regions are fabricated using MCVD and solution doping in a fused silica preform, the non-circular interface between the second and third claddings is obtained by inserting a series of rods into holes drilled at the core-cladding interface of a silica preform with a fluorosilicate outer cladding layer, and a final preform is prepared by inserting the first preform into a hole in the second preform that is concentric with its outer diameter.

The fiber of the present invention is sufficiently asymmetric that it allows radiation propagating in the multimode waveguide to be efficiently absorbed in the core, yet sufficiently symmetric that it can be handled like conventional round fiber.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross sectional illustration of an optical fiber having a core and three claddings, in accordance with the present invention;

FIG. 2 illustrates the propagation of light rays in a conventional round optical fiber; and

FIG's. 3a - 3c are a series of cross sectional illustrations demonstrating steps for producing a noncircular waveguide embedded in a round glass fiber.

DETAILED DESCRIPTION OF THE INVENTION

While the specification concludes with claims defining the features of the invention that are regarded as novel, it is believed that the invention will be better understood from a consideration of the following description in conjunction with the drawing figures, in which like reference numerals are carried forward.

A conventional all-silica double-clad fiber consists of a doped core with a diameter less than 10 μm and a numerical aperture greater than 0.10, surrounded by a fused silica multimode waveguide with a diameter near 100 μm with a numerical aperture (n) of 0.22, defined by an outer cladding of fluorine doped silica with n = silica - .017.

In the case of YbEr fibers, the optimum area for the multimode waveguide depends on the pump wavelength and the desired performance. For 1047 nm-like performance with a 950 nm pump the area ratio would have to be 60. For 1064 nm-like performance with a 975 nm pump an area ratio of 1250 would be acceptable. A typical value of 100 is consistent with typical pump diodes, single-mode core diameters, and multimode fiber numerical apertures. For example, the core diameter of a typical single-mode fiber at 1550 nm (Corning SMF-28) is 8.3 μm, leading to a multimode waveguide diameter of 83 mm. A typical 1 Watt (W) laser diode has an aperture of 100 mm and a numerical aperture of 0.13; assuming a (typical) silica multimode fiber numerical aperture of 0.22, this can be focused into a 60 μm fiber. The

difference between 60 μm and 83 μm can be used to accommodate any mechanical tolerances and aberrations in the coupling optics.

The choice of core size is dependent upon which one of many attributes one wishes to emphasize in a particular application. In low power amplifiers, it is usually desirable to minimize the core diameter, D, in order to reduce the saturation power to the lowest possible value. This maximizes efficiency and allows the amplifier to operate with low input powers. In a high power amplifier, particularly one used for video applications, the input signal is usually much larger than the amplifier saturation power, and the issue of core size is less important. In fact, it is often desirable to maximize the core size to reduce the possibility of optical damage or to simplify splicing to conventional fibers. The optimum core size is then limited by the bending losses associated with large, low numerical aperture (NA) fibers. Since this is the same issue that determines optimum core sizes in standard telecommunication fiber, it appears that a similar fiber size (e.g. D = 8.3 μm and a 0.12 NA for SMF-28) would be optimal. In the case of double clad amplifiers, maximizing the doped core area maximizes the allowable size of the multimode waveguide, which in turn allows the use of larger, more powerful pump diodes, or less demanding alignment tolerances.

To maximize the diameter of the doped core, it is necessary to maximize the diameter of the fundamental mode. In ordinary single mode fiber, this is done by making a larger core with a smaller numerical aperture. The usual way of doing this is to reduce the refractive index of the core. Unfortunately, in Yb Er co-doped fibers, the refractive index of the core is fixed at n_1 = silica + .013 by the phosphorous and rare earth doping requirements. With a silica cladding, this gives a numerical aperture of approximately 0.20, resulting in a single mode waveguide diameter of 5.5 μm for cutoff at 1450 nm. In principle, the numerical aperture can be reduced by increasing the cladding refractive index. Decreasing the NA to a value of 0.12 would require a cladding index of n_2 = silica + .008. In a typical geometry, where the core is prepared by modified chemical vapor deposition (MCVD) and solution doping, this would suggest the use of a doped starting tube with

a larger-than-normal refractive index. Unfortunately, such starting tubes are not readily available, so such an approach is not immediately practical.

A more practical alternative for increasing the core area is to consider a multilayer core configuration. Referring now to FIG. 1, there is illustrated therein a cross-sectional view of an optical fiber 10 having a core 12, and three claddings 14, 16, and 18 respectively. Each of the core and respective claddings will be discussed in greater detail below. As illustrated in FIG. 1, a layer of doped material corresponding to cladding 14 may be deposited between cladding 16, such as a silica starting tube, and the YbEr doped core 12. If this layer of doped material is thick enough, and is fabricated of the right materials, then the properties of the fundamental radiation mode will be determined only by the core index and the surrounding index pedestal.

More particularly, the core 12 may be fabricated of any of a number of core materials known in the art, preferred materials being Yb-Er doped optical fibers which may further include a doping material such as phosphorous and/or cesium, among others. The first cladding region 14, also referred to as the pedestal, is as described above, one or more layers of doped material. For example, cladding 14 may include a first doped layer 20 and a second doped layer 22. One preferred function of the first cladding 14 is to have a higher index of refraction than the silica starting tube (cladding 16), though less than the core 12. As such, layer 22 may be fabricated of any one or more materials well known in the art, an example of which is germanium.

Layer 20 may likewise have a reflective property or may be adapted to perform other functions. Hence, in FIG. 1, layer 20 may be fabricated of a material which absorbs or strips undesirable modes of light. Accordingly, layer 20 may be fabricated of a cobalt containing material. Other functions (and materials) may be employed as both layers 20 and 22. Moreover, it is important to note that cladding 14 may also be eliminated in certain applications.

Disposed about cladding 14 is second cladding 16, which is typically fabricated of a layer of pure or modified silica material 24, or other material as is well known in the art. The third cladding layer 18 is disposed about the

outside of the second cladding layer 16, and is typically fabricated of a fluorine doped silica material 26, and is the outer covering for the optical fiber.

Typical refraction index profiles for the core and claddings are also shown in FIG. 1, and below.

	CORE	Cladding 14	Cladding 16	Cladding 18
Diameter in µm	8.3	20	90	125
Refractive Indices	1.457	1.453	1.444	1.427

The optical modes typical of the structure of FIG. 1 can be calculated from the usual Bessel functions, and the effective indices and power densities can be calculated for each mode. The modes can be labeled by their effective indices as core modes ($n_1 > n_{eff} > n_2$), pedestal modes ($n_2 > n_{eff} > n_3$), and waveguide modes ($n_3 > n_{eff} > n_4$). The latter two groups are collectively referred to as cladding modes.

Table 1 gives the effective indices and the distribution of the modal power or modes (HE) in both the core and pedestal modes, as well as the region defined by layer 20. The fraction of the power in this region can be used to estimate how losses in this region will affect the various modes.

Table 1

Properties of the core and pedestal modes at 1550 nm for the fiber shown in FIG. 1.

	n_{eff}	Core $0 < r < 4.15$	Pedestal $4.15 < r < 10$	Edge $8 < r < 10$
HE_{11}	1.45407	.7783	.2208	.0053
HE_{21}	1.45084	.3428	.6400	.0960
HE_{12}	1.44876	.1642	.7484	.3014
HE_{31}	1.44820	.0807	.8477	.2520
HE_{22}	1.44652	.3049	.5226	.3269
HE_{41}	1.44596	.0158	.8336	.3710

The fundamental (HE_{11}) mode is well-approximated by a Gaussian with a $1/e^2$ radius $w_0 = 5.3$ mm, nearly identical to conventional single mode fiber, such as SMF-28. However, the fiber is single-mode only in the sense that there is only one guided core mode, and that its n_{eff} is sufficiently different from the other modes that any direct form of mode coupling is unlikely. It is not a true single-mode fiber because of the existence of guided cladding modes. The fact that some of these modes have appreciable overlap with the core 12 can complicate the performance of an amplifier using this fiber.

One potential difficulty with having higher order guided modes is coupling loss. If there were appreciable mismatch between the fundamental modes of the two fibers, then there would likely be significant power coupled to higher order modes. In the fiber described here, however, the pedestal region has been designed to produce a fundamental mode that very closely resembles that of conventional single-mode fiber. Mode overlap arguments suggest that most of the incident power will be coupled to the fundamental mode. Nonetheless, fiber misalignments and imperfections will always result in some power being coupled into other guided modes. This power likely to be concentrated in modes such as the HE_{22} mode which, as can be seen in Table 2, has appreciable overlap with the core region. In an amplifier, these modes are likely to experience appreciable gain. The difficulty with this is that the amplified pedestal signal can be remixed with the fundamental mode signal by imperfections in the output splice. This has the potential for introducing multipath distortions into the optical signal, something that is usually intolerable in, for example, a video system. Other problems, such as gain depletion by cladding mode ASE may also occur, but they are likely to be less significant than multipath signal distortion.

One way of avoiding this problem is to selectively attenuate the pedestal modes at the signal wavelength. As shown in Table 1, the fundamental mode intensity decreases rapidly outside the core region, and is almost negligible in the edge regions of the pedestal. Most of the higher order modes have significantly higher power density in this region. If the edge

region, i.e., layer 20, is doped, as described above, to be absorbing at 1550 nm, then the higher order modes will be attenuated without perturbing the fundamental mode. This absorbing region will act like the mode stripping coatings on conventional single-mode fiber, and will make the double clad fiber effectively single-mode at 1550 nm.

The choice of dopant is limited by the need for transparency at 950 nm. Dopants with the correct spectroscopic properties include Tb^{3+}, Co^{2+}, OH^- and B_2O_3. To minimize the doping level, and resulting index perturbation, a strongly absorbing dopant is desirable. Of the dopants listed, either Co^{2+} or Tb^{3+} appear to have the strongest contrast ratio (see Ainslie, et al. J. Lightwave Technology, 6, 287-293, 1988), while Co^{2+} is the most strongly absorbing. Co^{2+} is the ion used in filter glasses such as Schott BG-3, which attenuate at 1550 nm with negligible loss at 950 nm. In fused silica, the absorption has a value of 0.4 dB/m/ppmw. (P.C. Schultz, J. Am. Ceram. Soc., 57, 309, 1974). A Co^{2+} concentration of approximately 100 ppmw in the edge region would give a loss of approximately 0.2 dB/m for the fundamental mode, 3.8 dB/m for the HE_{21} mode and much higher losses for the other modes. This would appear to be consistent with use in an amplifier with a few meters of fiber. Co^{2+}-induced loss at 950 nm is expected to be less than 0.01 dB/m.

Co^{2+} can be introduced into the preform using conventional solution doping techniques. The existence of volatile compounds like $Co(CO)_3NO$ suggests that MCVD may ultimately be possible. A solution doped fiber would presumably be made by depositing a germanosilicate or aluminosilicate frit on the inside of the starting tube. After solution doping and sintering, this layer would have, for example, a Co^{2+} concentration of approximately 100 ppmw and a refractive index equal to that of the germanosilicate layers that are then added to make the remainder of the pedestal region. Once these layers are in place, the Yb Er core is deposited by conventional means. Note that this technique can be used in any double clad fiber, and need not be limited to round or silica clad designs.

Potential problems would be variations in the Co^{2+} doping, index mismatches between the Co^{2+} doped region and the rest of the pedestal, and the possibility of Co^{2+} migration into regions where it will attenuate the fundamental mode.

The Co^{2+} doped absorbing region of layer 20 can be used to eliminate problems at the signal wavelength, but there are also potential problems at the pump wavelength. The pedestal forms a waveguide with radial symmetry, and the higher order modes do not interact strongly with the core. This problem is minimized by keeping the pedestal small. All the modes in Table 1 have more than 1% of their power in the core region, so their absorption efficiency is no worse than for an average cladding mode. However, any further increase in the pedestal diameter would result in a group of modes with greatly reduced core interactions. This solution may not be possible for the waveguide modes, where a much larger waveguide area is required. Instead it is necessary to eliminate the radial symmetry of the waveguide.

Referring now to FIG. 2, there is identified therein the propagation of light rays, e.g., 30, in a radially symmetric step-index fiber. FIG.s. 2a and 2b illustrates propagation of the waveguide modes in a round outer cladding fiber 32, and forms the starting point for analyzing the nonsymmetric geometries as described below. The two angles q_z and q_f are defined in the drawing and are conserved on reflection. The propagation distance between reflections is given by $L_p = 2\ r \sin q_f / \sin q_z$, and the distance of closest approach to the core is given by $r_{ic} = r \cos q_f$. For a given value of q_z, ray propagation can be characterized by a ray trace in the projection plane where it can be seen in Fig. 2b that for a round fiber, r_{ic} is invariant.

The modes of this fiber can also be described. Ignoring polarization effects, and assuming a low enough NA to allow the weak guidance approximation to be valid, the bound modes in the core are of the form $Y(r,f) = J_l(r/r_{lm}) \exp(-ilf)$, where $J_l(r/r_{lm})$ is the Bessel function of the first kind of order l, where l can have positive or negative values, where $f \equiv q_f$, and r_{lm} is a parameter determined from the boundary conditions for the radial wave. Note that there may be several values of m associated with each value of l,

and that the total (finite) number of bound modes will scale with the area and NA of the fiber.

Modes with nonzero values of l have zeros at r = 0, so they will not interact strongly with an absorbing core located there. A radially varying perturbation is required to couple these modes to the modes with l = 0. The allowable variation in fiber radius is limited by the need to have a round fiber that can be spliced to a round multimode pump fiber. An inner radius r_0 is chosen to be greater than or equal to the radius of the pump fiber. A radially varying positive perturbation dr(f) is added to the diameter such that its maximum value, dr_{max}, gives a value of $r_0 + dr_{max}$ less than the outside fiber radius, minus the cladding thickness. Typically, $0.05 < dr_{max}/r_0 < 0.20$, with 0.10 being a typical value.

The modes for these waveguides are difficult to calculate, except in a few special cases. For example, consider $dr(f) = r_0 [1 - \sec((1/2) \sin^{-1}(\sin (2f)))]$, corresponding to a square waveguide, with $dr_{max}/r_0 = .41$. The modes are of the form f(x)g(y), where f and g are sines or cosines. Because of the cosine terms, 25% of the modes have maxima at the fiber center. This is not ideal, because the remaining 75% of the modes have minima at the center and will not be absorbed without additional mode mixing. However, this shows that fibers with lower symmetry can have stronger absorption.

In a few cases, it is practical to calculate the modes of the fiber perturbed by dr(f) using perturbation theory. This gives modes as linear combinations of the unperturbed modes. We are interested in the coefficients that mix modes with nonzero values of l with modes with l = 0. If dr(f) is small, then the variations in the Y_{lm} (r,f) are negligible in the interval defined by dr(f). T he coefficient coupling larger values of l to l=0 is then proportional to $\int_0^{2\pi} dr(f) \exp(-ilf)\, df$. If dr(f) is described by a real Fourier series, $dr(f) = \sum_{j=-\infty}^{\infty} c_j \exp(ijf)$, where $c_j^* = c_{-j}$, then the coupling coefficient is proportional to c_l, Thus, mode coupling in these fibers is determined by the spatial frequencies of the radial perturbations in the fiber. For purposes of

absorption, it is important to identify the modes that are least efficiently coupled to the $l = 0$ modes, since the fiber length will have to be adjusted to allow these modes sufficient interaction length to be absorbed. These would be associated with small values of c_l that cause modes to interact weakly with the core, causing the effective absorption coefficient to be small.

This perturbation approach is impractical for all but very small values of dr(f) because it requires detailed enumeration of all the modes of the fiber. Larger perturbations can be best analyzed using geometric optics. In terms of ray optics, the perturbations that couple modes with different values of l are equivalent to perturbations that cause rays to change values of r_{ic}. For absorbing fibers, the important parameter is the propagation interval in which all rays that start with large values of r_{ic} pass at least once through small values of r_{ic}. Since q_z is conserved in a straight fiber, the pathlength in the projection plane is proportional to the propagation length. Thus the propagation of rays can be characterized by a two dimensional ray trace in the projection plane, with the appropriate figure of merit being related to the pathlength in this plane normalized to r_0. Practical evaluation of fiber shapes can be achieved by considering an ensemble of rays launched with large r_{ic} (for example, $r_{ic} > 0.9\ r_0$) and then propagating these rays in the plane until a large fraction (for example, 90% of the rays) has passed at least once along a trajectory with a small value of r_{ic} (for example, $r_{ic} < 0.1\ r_0$). The figure of merit L_{90}/r_0 for the perturbation is then the normalized pathlength in the projection plane required to achieve this.

The first shapes to consider are regular polygons. A simple analytical model can be derived by noting that, for a regular polygon with N sides, each reflection changes the skew angle of a ray from f to something in the range f±p/N. After M uncorrelated reflections, this would evolve into a Gaussian distribution centered at f with standard deviation of $s=(p/N)(M/3)^{1/2}$. When s >p/2, or when $M >> 3N^2/4$, this corresponds to uniform illumination, independent of the original value of f. Consequently, one might expect that L_{90}/r_0 will increase as the square of the number of sides.

Table 2 gives values of L_{90}/r_0 as a function of the number of sides calculated on the basis of 200 rays launched with $r = .95 \pm .05$. As Monte Carlo simulations, these results contain statistical uncertainties of at least ±10%, but they give an idea of the relative performance of the different shapes. One observation is that the performance of the triangular and pentagonal shapes are nearly identical. A second observation is that while L_{90}/r_0 increases with the number of sides, it is not a smooth quadratic function. The even and odd values larger than 4 do scale approximately quadratically, but the even-sided polygons appear to be twice as efficient as their odd-sided counterparts. Furthermore, the calculated values for the three and four sided figures are significantly larger than the values extrapolated from larger polygons.

Table 2.

Figures of merit for mode mixing in regular polygonal fibers.

Number of sides	3	4	5	6	7	8	9	10
L_{90}/r_0	54	46	56	42	119	73	184	132
dr_{max}/r_0	1.00	.414	.236	.155	.110	.082	.064	.051

Polygons are not especially well adapted to the problem of making all-silica nearly-round fibers with small values of dr_{max}. The first polygon to have $dr_{max}/r_0 < .1$, for example, is an octagon. This is a potentially useful shape, since it gives a figure of merit only slightly worse than that of the triangular fiber. Furthermore, the fiber has a centered core and has equal radii across any two perpendicular directions. These features make this shape distinctively different from those considered by Snitzer, et al. and Po, et al. The problem with this shape is fabrication. Polymer clad rectangular fibers have been made by grinding the preform to the desired shape and then drawing the fiber near enough its softening point that the shape is preserved. The polymeric cladding is then coated onto the fiber where it conforms to the existing shape. The equivalent fabrication process for an octagon is greatly complicated by the larger number of sides to be ground. It is also difficult to

make all-silica polygonal fibers, since there is no readily apparent process analogous to the low-index organic coating that produces a conforming low index silica cladding.

One technique that is conventionally used to introduce asymmetry into fibers is gas phase etching. This is the process used to produce "bow-tie" birefringent fiber. By etching a series of channels into the inside diameter of a low index tube and then collapsing the tube over a silica preform, a surface approximating a sinusoidal surface with $dr(f) = (dr_{max}/2)(1\text{-}Cos[nf])$, might be fabricated. For odd values of n, this fiber is "circular" in the sense that $r(f) + r(f + p) = 2\, r_0 + dr_{max}$ for all values of f. Values of L_{90}/r_0 for this geometry with $dr_{max}/r_0 = .1$ are given in Table 3. For n = 1 the shape closely approximates an off-center circular fiber and for n = 2, it closely approximates an elliptical fiber with an eccentricity of 1.1. These shapes closely approximate the shapes recommended by Snitzer, et al., and, in this case, neither one appears to work very well. On the other hand, the performance for n > 5 can be as good or better than that obtained from the polygonal shapes.

Table 3.

Figures of merit for mode mixing in sinusoidal fibers.

n	1	2	3	4	5	6	7	8	9	10
L_{90}/r_0 for $dr_{max} = .1r_0$	>999	>999	>999	163	60	37	48	39	40	46

Unfortunately, the gas-phase etching technique is best suited to a two or three lobe figure, and it would be quite difficult to fabricate the more-efficient shapes with larger values of n. Alternative shapes that are more readily fabricated would be desirable.

Referring now to FIG.s 3A-3C, there is illustrated therein a process by which asymmetries can be introduced into optical fibers such as that identified in FIG. 1 with rod-in-tube fabrication techniques. This technique is used, for example, to produce birefringent fibers. FIG. 3A shows a

conventional preform for an all silica multimode fiber. In this preform, the silica core 40 is overlaid with a layer of fluorine doped silica 42. Such preforms are available commercially from Hereus. In FIG. 3B, eight vias 44-58, each with a radius of, for example, $r_b = 0.2r_0$ and $dr_{max}/r_0 = 0.1$ have been made in this preform 40 using, for example, an ultrasonic mill. The vias 44-58 may be circular holes as illustrated in FIG. 3B, or some other shape. The vias are simply present to introduce irregularities into the shape of preform 40. Undoped silica rods may then inserted into these holes to produce the profile shown in FIG. 3C. Thereafter, the core and pedestal region such as described hereinabove with respect to Fig. 1, may be introduced into the preform of FIG. 3C.

The result is an optical fiber having a central core region appropriately doped to absorb radiation and provide gain at preselected wavelengths. Disposed around the core may be a first region adopted to modify or strip modes in light introduced into the core. Around the first region is disposed a first cladding layer found of for example, silica, and having a radially constrained, substantially non-circular outer boundary. By radially constrained substantially non-circular, it is meant that the outside surface of the first cladding layer is generally round in cross-section and tubular overall, but due to the pattern of predefined irregularities manufactured into the cladding the outer boundary does not define a smooth, regular circle or tube. Thereafter, disposed around the first cladding layer is a second cladding layer having an inner boundary which conforms to the outer boundary of the first cladding layer, and a regular round outer boundary.

The effectiveness of this design illustrated in FIG. 3 is determined by both the size and number of holes. Accordingly, the instant invention is not limited either by the number of holes deposited herein, nor by the hole sizes. Rather, any number of variably sized holes may be appropriate for a given fiber application. Table 4 gives calculated figures of merit for different hole arrangements. For a given hole size, the figure of merit decreases almost linearly with the number of holes. This is to be expected, since any reflection from the original round surface causes no change in r_{ic}. Since each new hole or

irregularity reduces the amount unperturbed surface, it also reduces the time that each ray spends "idling" at a particular value of r_{ic}. Larger vias or holes also contribute to this effect because each via hole occupies a larger fraction of the fiber circumference. However, for a given circumference, a larger number of smaller holes is more effective, as can be seen by comparing the bracketed values in Table 4.

Table 4.

Figures of merit for different hole diameters in the geometry shown in figure 3 with $dr_{max}/r_0 = .1$.

Number of holes $dr_{max}=.1r_0$	1	2	3	4	5	6	7	8	9	10
L_{90}/r_0 for $r_b/r_0 = .1$	610	303	242	143	107	133	129	131	110	[72]
L_{90}/r_0 for $r_b/r_0 = .2$	685	255	221	163	[136]	109	86	75	73	76
L_{90}/r_0 for $r_b/r_0 = .3$	494	238	[155]	112	93	75	73	60	(58)	(52)
L_{90}/r_0 for $r_b/r_0 = .4$	324	169	126	107	88	(53)	(46)	(50)	(45)	
L_{90}/r_0 for $r_b/r_0 = .5$	317	169	110	(80)	(69)	(58)	(56)	(51)		

The values in parentheses () cannot be fabricated by rod-in-tube methods due to interference between adjacent rods. Values in brackets [] represent shapes with approximately equal unperturbed circumferences. Smaller values correspond to better performance.

It can be inferred from the data in Table 4 that the performance of the fibers improves with the number of holes, and that if enough small holes are used, the performance will match or exceed that of the best of the polygonal fibers. Unfortunately, there are limits to the size and number of holes that can be made. Many of the best values in Table 4 are in parentheses, indicating that they are fabricated by commercially impractical methods, and cannot be fabricated by rod-in-tube methods due to interference between adjacent rods. Other potentially efficient combinations are not even shown because they require an impractically large number of holes. More elaborate (and costly) fabrication techniques can be imagined, where one set of rods is inserted and the preform fused before a second set of holes are made, but such techniques may well be impractical.

There are, however, several feasible combinations of hole sizes and diameters that can be used to achieve performance similar to that observed previously with the octagon. In particular, a set of 8 holes with $r_b/r_0 = 0.2$

closely mimics the performance of an octagon, including the properties of a centered core in a fiber that does not have differing orthogonal radii. The combinations involving fewer, larger holes may be easier to fabricate, simply because there are fewer holes to make. In particular, the combination of 4 holes with r_b/r_0= .4 may be a more practical, if somewhat less efficient alternative. If space is available, then increasing the value of dr_{max}/r_0 to 0.2 will improve the efficiency somewhat, as shown in Table 5.

Table 5

Figures of merit for the geometry shown in Fig. 3 with r_b/r_0 = .4 and dr_{max}/r_0 = 0.2.

Number of holes dr_{max}=.2r_0	1	2	3	4	5	6	7	8	9	10
L_{90}/r_0 for r_b/r_0 = .4	303	160	108	71	71	(61)	(55)			

(The values in parentheses () cannot be fabricated by rod-in-tube methods due to interference between adjacent rods.)

Another approach to the problem is to leave the core diameter intact but to introduce perturbations into the fiber index. This could be done, for example, by inserting rods with higher refractive index in place of the silica rods in FIG. 3. These rods would act as cylindrical lenses, refocusing the skew rays to new values of r_{ic} just like the cylindrical mirrors in the previous technique. An advantage of this technique is that the rods do not need to extend outside of the round cladding boundary, but instead will be effective if they are merely tangent to the interface. There are some limitations to this technique. A rod of radius r_b that has a focal length r_b / 2 as a reflector, has a focal length of (r_b / 2)(n/ Δn) as a refractive rod with index n + Δn, where n is the refractive index of the original material. Since in most practical cases, $\Delta n \ll n$, the reflector will be much more strongly focusing than the lens, and effectiveness of the refractive technique will be much lower than that of the reflective technique. Nonetheless, it may provide a practical alternative in some cases, especially if large values of Δn are achievable.

A second related technique is to introduce stresses into the first cladding region so that the stress-induced index changes perturb the skew ray trajectories. Stresses could be introduced by adding stress members such as inserted borosilicate rods to the region outside the waveguide. This has the advantage that the perturbations are all external to the guiding region, so that no extra losses will be introduced. Stress introduces both index changes and birefringence, and both can perturb the ray trajectories. The index changes will produce lensing analogous to that produced by the rod lenses, although shapes of the index distortions are unlikely to be conveniently round and lens-like, so the exact deflections will be difficult to calculate. Birefringence can cause the reflections to occur at angles different from the usual law of reflection. This is analogous to double refraction. The magnitude of the index changes that can be achieved by stress is quite small, as distortions large enough to change the material density appreciably also tend to cause fracture in a brittle material like glass. Thus, it is unlikely that the perturbations achieved by this technique will be as effective as those created by the reflective technique. Nonetheless, it may be a useful technique in some cases, especially when loss is an important issue.

EXAMPLES

A cladding pumped YEDFA:

In principle, a 1 watt laser diode at 950 nm (model 6360 from SDL Inc., San Jose, CA) can be coupled to 60/125, 0.22 NA, all-silica multimode fiber with an efficiency approaching 100%; an actual coupling efficiency of at least 80% is reported using a lens system sold by LIMO-Lissotschenko Mikrooptik, GmbH, Dortmund, Germany. This produces an 800 mW output that can then be relayed through a pair of graded refractive index lenses (Selfoc GRIN lenses made by Nippon Sheet Glass Ltd., Tokyo, Japan) into an 80/125, 0.22 NA, all-silica multimode fiber. The increase in fiber diameter is required to accommodate spherical aberration in the GRIN lenses. Note that this is equivalent to the imaging system found in the filter wavelength division multiplexer (FWDM) made by E-Tek Dynamics Inc. of San Jose CA, where a

single GRIN lens and a reflector are used to couple a pump fiber to an adjacent output fiber. Although this imaging system was intended for single-mode fiber, it should, allowing for some aberrations, work equally well for multimode fibers.

The other input to the FWDM is a single-mode fiber (SMF-28), whose output is collimated with a second GRIN lens, transmitted through the (dichroic) reflector and refocused into the (ordinarily SMF-28) output fiber. If the output fiber of the FWDM is replaced with a double-clad gain fiber with a NA of 0.22, $r_0 = 40$ mm, a fundamental mode matched to SMF-28, and an outside diameter of 125 mm, then both inputs to the FWDM will be coupled to the output fiber, which will serve as an amplifier.

A multimode preform can be obtained from Hereus-Amersil, Inc, (Duluth, GA) where a fused silica rod with a diameter of 20 mm is surrounded by a 5.6 mm thick layer of a fluorosilicate material with a refractive index 0.017 lower than the undoped fused silica. Using an ultrasonic mill, 5 holes 6 mm in diameter are drilled parallel with the axis of the rod. One is centered on the axis, and the other four are symmetrically arranged with their centers 9 mm from the axis. The rods to be inserted in the 4 radial holes are made from fused silica. The rod to be inserted in the central hole is a preform made by MCVD and solution doping techniques. On the inside wall of a silica tube with a 0.5 mm wall thickness, a 0.5 mm thick germanosilicate frit is prepared and solution doped with Co^{2+} from an aqueous solution. This layer will have a Co^{2+} concentration of 100 ppmw and a refractive index 0.008 larger than pure fused silica. This layer is dried and sintered as usual and then a 1 mm thick germanosilicate layer with the same refractive index is applied over it. A phosphosilicate frit is then applied and solution doped with Yb and Er. This layer is dried and sintered, and then the preform is collapsed to its final 6 mm outer diameter. This tube is then inserted in the central hole and the entire preform is heated to fuse the rods into the holes. This preform is then drawn to a 125 mm outer diameter using conventional techniques. A length of 2 to 10 meters will be sufficient to absorb a 950 nm pump and will provide gain in excess of 50 dB.

A second example would be a higher power laser pumped at the absorption maximum of 975 nm to yield performance similar to a 1064 nm-pumped device. In this case, an area ratio of 1250 combined with an 8.3 mm core would permit the use of a 290 mm outer waveguide. This is well-matched to the 10 watt fiber-coupled diode bars manufactured by Opto Power Corporation of Tucson AZ, which emit from a 250 mm aperture with a NA less than 0.22. These devices are available at 975 nm, but must be temperature tuned to match the peak. The construction of the amplifier is similar to the previous device except that the outer waveguide of the fiber needs to be bigger. In addition, the larger fiber size may require some modification of the commercial FWDM.

While the preferred embodiments of the invention have been illustrated and described, it will be clear that the invention is not so limited. Numerous modifications, changes, variations, substitutions and equivalents will occur to those skilled in the art without departing from the spirit and scope of the present invention as defined by the appended claims.

What is claimed is:

<u>CLAIMS</u>

1. A optical fiber comprising:

a core region formed of a doped glass material, said core region adapted to absorb radiation at a first wavelength and provide gain at a second wavelength;

a first cladding layer having an outer boundary, and disposed around said core region, said first cladding layer having a plurality of irregularities found at least along said outer boundary; and

a second cladding layer having an inner and outer boundary, said inner boundary conforming to the outer boundary of said first cladding layer.

2. An optical fiber as in claim 1, wherein said core region is doped with an element selected from the group of Ce, Yb, Er, P, and combinations thereof.

3. An optical fiber as in claim 1, wherein said first cladding layer is fabricated of glass.

4. An optical fiber as in claim 3, wherein said glass is a doped or undoped silica glass.

5. An optical fiber as in claim 1, wherein said irregularities interrupt the propagation of radiation entering said first cladding layer.

6. An optical fiber as in claim 1, wherein said outer boundary of said first cladding layer is a radically constrained, non-circular outer boundary.

7. An optical fiber as in claim 1, wherein said irregularities are a series of protrusions extending away from said core region.

8. An optical fiber as in claim 7, wherein said protrusions are a plurality of semi-circular protrusions.

9. An optical fiber as in claim 1, wherein said irregularities are a series of stressed regions introduced into said first cladding layer.

10. An optical fiber as in claim 1, further comprises an intermediate cladding layer between said core region and said first cladding layer.

11. An optical fiber as in claim 10, wherein said intermediate cladding layer has a different refractive index than that of said core region.

12. An optical fiber as in claim 11, wherein said intermediate cladding layer is adapted to eliminate unwanted modes in said radiation.

13. An optical fiber as in claim 11, wherein said intermediate cladding layer comprises a plurality of sub-layers.

14. An optical fiber as in claim 13, wherein a first sub-layer is adapted to propagate radiation along said core region, and a second sub-layer is adapted to eliminate unwanted modes in said radiation.

15. An optical fiber comprising:

a centrally disposed core region adapted to absorb radiation at a first wavelength and provide gain at a second wavelength, said radiation having at least one mode;

an intermediate cladding layer disposed around said core region, said intermediate cladding layer eliminating modes in said radiation;

a first cladding layer having an outer boundary and disposed around said intermediate cladding layer, said first cladding layer having a plurality of irregularities formed at least along said outer boundary; and

a second cladding layer disposed around said first cladding layer.

16. An optical fiber as in claim 15, wherein said core region is doped with an element selected from the group of Ce, Yb, Er, P, and combinations thereof.

17. An optical fiber as in claim 15, wherein said first cladding layer is fabricated of glass.

18. An optical fiber as in claim 17, wherein said glass is a doped or undoped silica glass.

19. An optical fiber as in claim 15, wherein said irregularities interrupt the propagation of radiation entering said first cladding layer.

20. An optical fiber as in claim 15, wherein said outer boundary of said first cladding layer is a radically constrained, non-circular outer boundary.

21. An optical fiber as in claim 15, wherein said irregularities are a series of protrusions extending away from said core region.

22. An optical fiber as in claim 21, wherein said protrusions are a plurality of semi-circular protrusions.

23. An optical fiber as in claim 15, wherein said irregularities are a series of stressed regions introduced into said first cladding layer.

24. An optical fiber as in claim 15, wherein said intermediate cladding layer has a different refraction index than that of said core region.

25. An optical fiber as in claim 15, wherein said intermediate cladding layer comprises a plurality of sub-layers.

26. An optical fiber as in claim 25, wherein a first sub-layer is adapted to propagate radiation along said core region, and a second sub-layer is adapted to eliminate unwanted modes in said radiation.

27. An optical fiber comprising:

a central core region adapted to absorb radiation at a first wavelength and provide gain at a second wavelength, said radiation having at least one mode;

an intermediate cladding layer disposed around said core region, said intermediate cladding layer having a plurality of sub-layers;

a first cladding layer having a radically constrained, non-circular outer boundary, and disposed around said intermediate cladding layer; and

a second cladding layer disposed around said first cladding layer.

28. An optical fiber as in claim 27, wherein said core region is doped with an element selected from the group of Ce, Yb, Er, P, and combinations thereof.

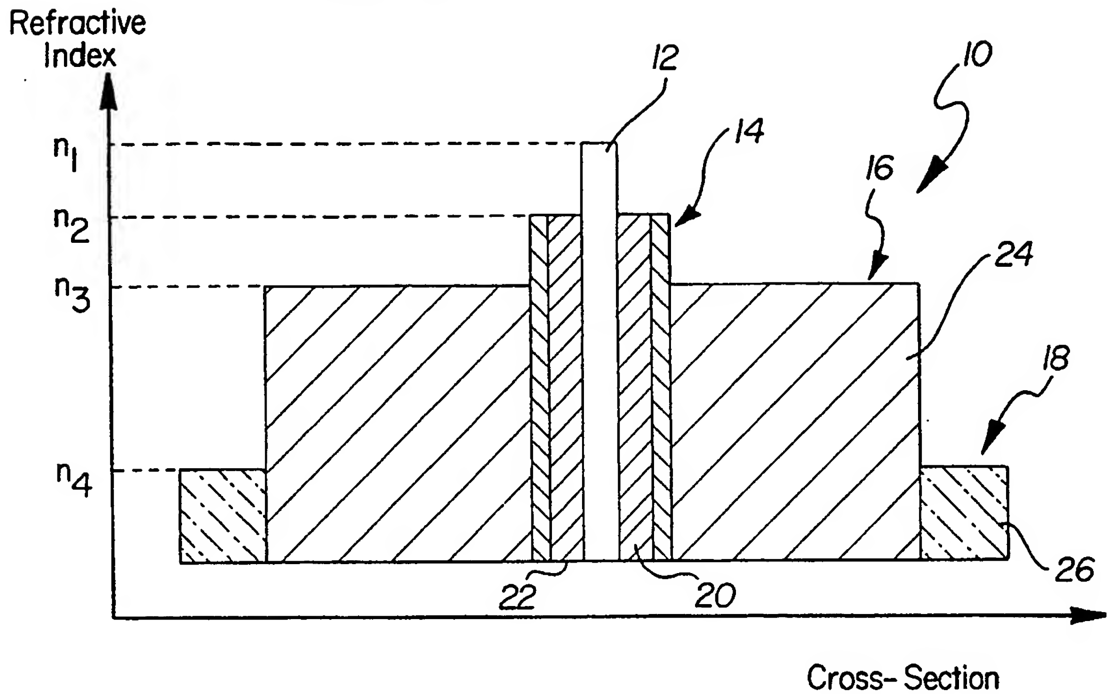
29. An optical fiber as in claim 27, wherein said glass is a doped or undoped silica glass.

30. An optical fiber as in claim 27, wherein said protrusions are a plurality of semi-circular protrusions.

31. An optical fiber as in claim 27, wherein said intermediate cladding layer has a different refractive index than that of said core region.

32. An optical fiber as in claim 27, wherein a first sub-layer is adapted to propagate radiation along said core region, and a second sub-layer is adapted to eliminate unwanted modes in said radiation.

FIG-1


Refractive Index
n_1
n_2
n_3
n_4
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10
14
16
24
18
26
22
20
Cross-Section

FIG-2A

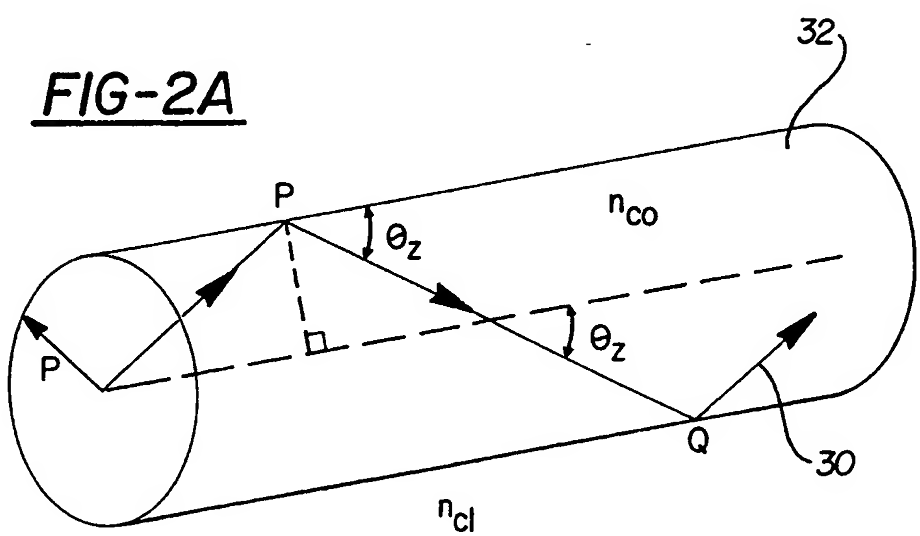

32
P
n_{co}
θ_z
θ_z
P
Q
30
n_{cl}

FIG-2B

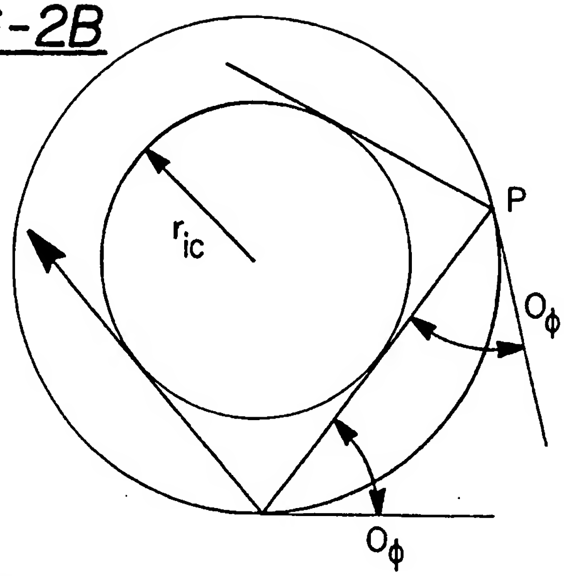


FIG-3A

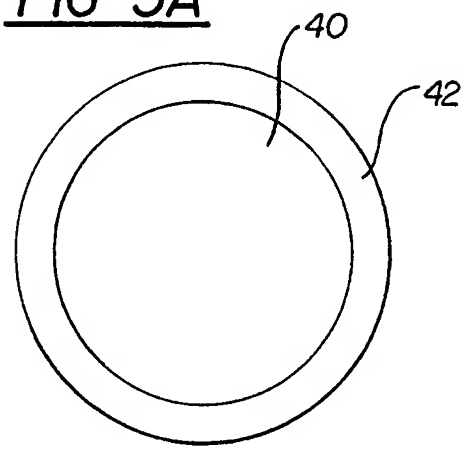
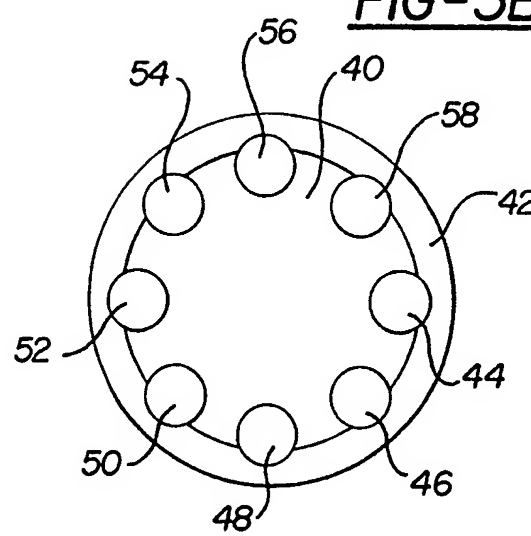


FIG-3B



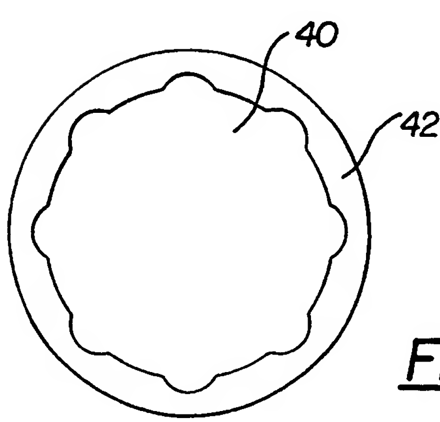


FIG-3C

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/25943

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/06 G02B6/22

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	EP 0 776 074 A (AT & T CORP) 28 May 1997 see figure 1 see column 6, line 40 - column 7, line 29 ---	1-8 10-12, 15-22, 24,27-31
Y	US 5 121 460 A (HAKIMI FARHAD ET AL) 9 June 1992 see the whole document ---	10-12, 15-22, 24,27-31
X A	PATENT ABSTRACTS OF JAPAN vol. 097, no. 003, 31 March 1997 & JP 08 313749 A (FUJIKURA LTD), 29 November 1996 see abstract ---	1-9 15-23, 27-30

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 March 1999	17/03/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Ciarrocca, M

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INTERNATIONAL SEARCH REPORT

Int ·ional Application No
PCT/US 98/25943

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 010, no. 057 (P-434), 7 March 1986 & JP 60 200208 A (FUJITSU KK), 9 October 1985 see abstract -----	1

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 98/25943

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0776074 A	28-05-1997	JP 9194225 A	29-07-1997
		US 5873923 A	23-02-1999
US 5121460 A	09-06-1992	NONE	